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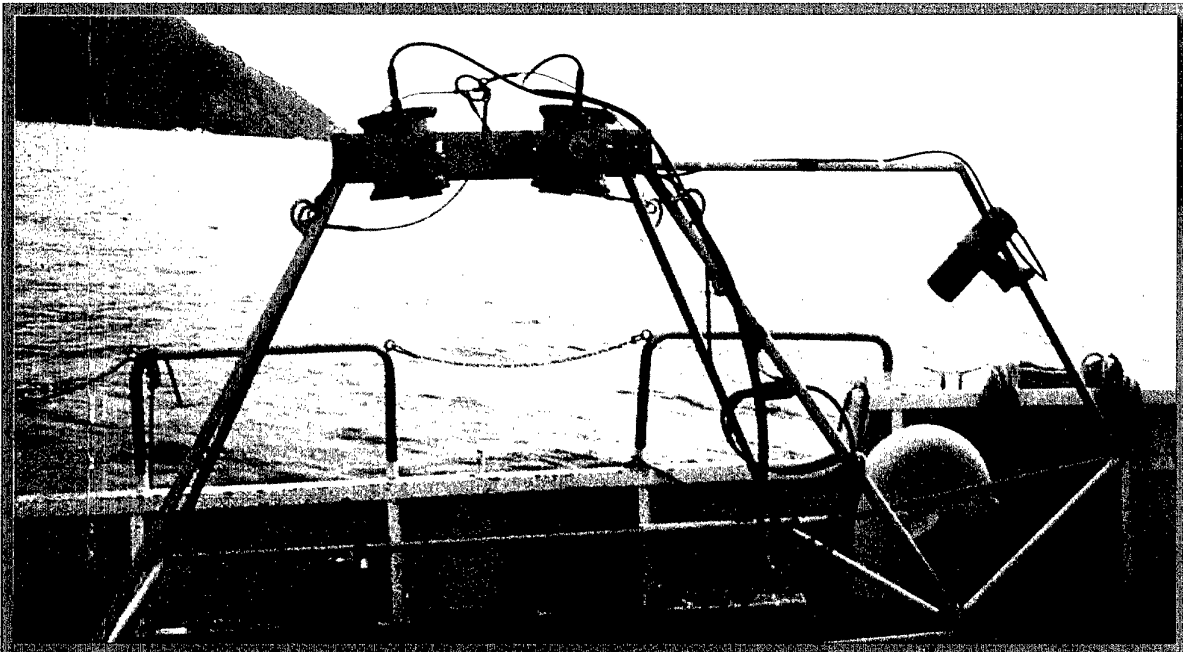

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Characterization of the two-dimensional roughness of shallow-water sandy seafloors

A. P. Lyons, W.L.J. Fox, T. Hasiotis, and E. Pouliquen

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Executive Summary:

The performance of MCM sonars is critically dependent on the characteristics of the seafloor. Detection performance is affected by the surface roughness as it affects the acoustic reverberation. Characterization of seafloor surface roughness and its dynamics is essential for understanding and quantifying the influence of sediment microtopography. Field measurements have been taken recently with an end-to-end digital photogrammetry system providing quantitative, two-dimensional seafloor surface roughness measurements on spatial scales of approximately a millimeter to a meter. Results of these measurements have shown that sediment surfaces in shallow water are often anisotropic and/or exhibit non-Gaussian height distributions, both of which have the potential to affect strongly high-frequency seafloor acoustic scatter. For these kinds of surfaces, simple roughness parameters such as rms height or the slope and offset of a power law representation of the power spectra will not give a sufficiently complete description. Two-dimensional statistical models are needed to capture the anisotropic nature of sediments with oriented features, while for seafloors with peaked forms, it is the phase information in the frequency domain that is required, as this controls the shape characteristics of a surface. Characterization of seafloor roughness based on these ideas is presented using results from the digital photogrammetry system. The characterization of seafloor roughness is an important input parameter to predictive models of high-frequency acoustic scattering. These models, in turn, are important components of MCM sonar performance prediction.

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Characterization of the two-dimensional roughness of shallow-water sandy seafloors

A.P. Lyons, W.L.J. Fox, T. Hasiotis, and E. Pouliquen

Abstract:

Surface roughness is a fundamental seafloor property affecting a variety of physical phenomena including sediment transport and the interaction of acoustic energy with the seafloor. Characterization of seafloor surface roughness and its dynamics is therefore essential for understanding and quantifying the influence of sediment microtopography. Field measurements have been taken recently with an end-to-end digital photogrammetry system providing quantitative, two-dimensional seafloor surface roughness measurements on spatial scales of approximately a millimeter to a meter. Results of these measurements have shown that sediment surfaces in shallow water are often anisotropic and/or exhibit non-Gaussian height distributions, both of which have the potential to affect strongly high-frequency seafloor acoustic scatter. For these kinds of surfaces, simple roughness parameters such as rms height or the slope and offset of a power law representation of the power spectra will not give a sufficiently complete description. Two-dimensional statistical models are needed to capture the anisotropic nature of sediments with oriented features, while for seafloors with peaked forms, it is the phase information in the frequency domain that is required, as this controls the shape characteristics of a surface. Characterization of seafloor roughness based on these ideas is presented using results from the digital photogrammetry system.

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Introduction

Although the roughness of the seabed is of great importance in studies of sediment transport, near bottom flow and high-frequency acoustic bottom scattering, few studies have quantitatively resolved seafloor microtopography at appropriate scales. Recent efforts to determine small-scale roughness have involved stereo photogrammetry, which has the advantages of high resolution and the potential for extracting two-dimensional surface information. During the High Energy Benthic Boundary Layer Experiment (HEBBLE), Swift et al. [1] first attempted and measured photogrammetrically in detail the size of certain deep-sea bedforms in 4700-5100 m water depth, but did not estimate the overall surface roughness. Briggs [2] compared height data from several shallow water (<50 m) sites with different texture and microtopography, computing rms-height statistics and spectra from one-dimensional microrelief profiles. Hollister and Nowell [3] analyzed photographs from the HEBBLE experimental area and observed, by examination of surface contours, temporal changes in seafloor roughness. Wheatcroft [4] presented a large amount of data (167 stereo-photographs) from the Sediment Transport Events on Shelves and Slopes (STRESS) project and studied in detail bed configurations, temporal changes and seabed relief for a silty bottom. Using stereo photography, Akal and Hovem [5] have also analyzed small-scale roughness of the seafloor, generating power spectra and autocorrelation functions. All of the datasets mentioned above were obtained using conventional (human and stereocomparator) analytical photogrammetric profiling techniques. Although it is possible to perform full two-dimensional (2-D) analysis on photogrammetrically derived sediment height values, due to the large time and effort involved in the use of conventional systems, only reduced estimates of roughness such as rms heights or one-dimensional roughness spectra are usually produced.

While one-dimensional analysis should be sufficient for isotropic roughness, it can be very limiting in the study of anisotropic seafloors. In areas of shallow-water exposed to the open sea, the surface morphology of coarse silt and/or sand sediments will necessarily be at times anisotropic, as the dominant roughness formation mechanism is directionally dependent. When the water depth is shallow enough, wave induced currents on the bottom will produce oriented sand ripples. The structure of ripples contains information about wave conditions and direction, water depth and environment. Symmetrical ripples, sometimes termed oscillation or wave ripples due to their known causative process, usually have sharp crests and rounded troughs, and are generally accepted a priori as produced by wave activity, although the common presence of symmetrical ripples in deep-sea photographs suggests other possible mechanisms. The orientation of the ripples can also suggest their origin in some cases. Because of the general absence of shoreward-flowing currents, it is generally inferred that ripples that face or migrate in a shoreward direction are solely the products of waves. Because troughs and ridges of neighboring ripple patches will generally not align, absolute regularity is not attained

over wide areas and the seafloor will not be perfectly corrugated. The system of ripples is seldom preserved when the wave forcing increases, so that the patterns we find are generally due to decreasing force. One form that can result from decreasing waves is that of major oscillation ripples with smaller crests in their troughs. Figure 1 displays a photograph taken of a rippled sandy seafloor (10 m water depth) and shows some of the features of naturally occuring ripples, including broad troughs and sharp peaks and the almost, but not quite, corrugated nature of the surface.

Once the currents due to wave forcing subside, the effects of another roughness modification mechanism that is operating continually will begin to make themselves evident. The sediment surface is continuously being modified by both animals that live on (epifauna) and within (infauna) the sediment. Locomotion and/or feeding activity of the animals redistributes the sediment changing the sediment surface profile. In addition to being a continuous process, bioturbation is cumulative and often isotropic, and due to the size of the organisms, will usually be on a different scale than that of hydrodynamic modifications. In general surfaces formed by a process that is cumulative, such as local bioturbation acting everywhere, will have statistics that are nearly Gaussian. The semi-organized ripple surfaces put down by waves will be randomized by bioturbation, eventually erasing the anisotropic structures that exist. Seafloor roughness is a dynamic process and a particular sediment surface can changes on scales of days or even hours [6] due to bioturbation. Even though the surface is continually changing, the underlying statistical description or roughness spectrum has been assumed to be relatively stable. In contrast, the spectrum of roughness for rippled shallow water seafloors should have strong time dependence.

This paper introduces the first results obtained for an anisotropic (rippled) seafloor, using an end-to-end digital stereo photogrammetric system. The field data used here were collected during two experiments undertaken by the SACLANT Undersea Research Center (SACLANTCEN). Both experiments took place at Elba Island, in Tuscany in western Italy. The first experiment was conducted in Biodola Bay in November 1997, in order to quantify the influence of directional seafloor ripples and beds of Posidonia Oceanica seagrass found in shallow waters, on high-frequency acoustic backscatter over a wide range of frequencies. For this purpose a large number of field data were collected, including backscatter and propagation measurements and environmental data. The second experiment was performed at Marciana Marina in December 1997. During that study (conducted primarily for acoustic penetration analysis) another set of digital stereo images and surface sediment samples were collected. Bottom digital stereo photographs, collected as part of the environmental data suites, are discussed and evaluated here.
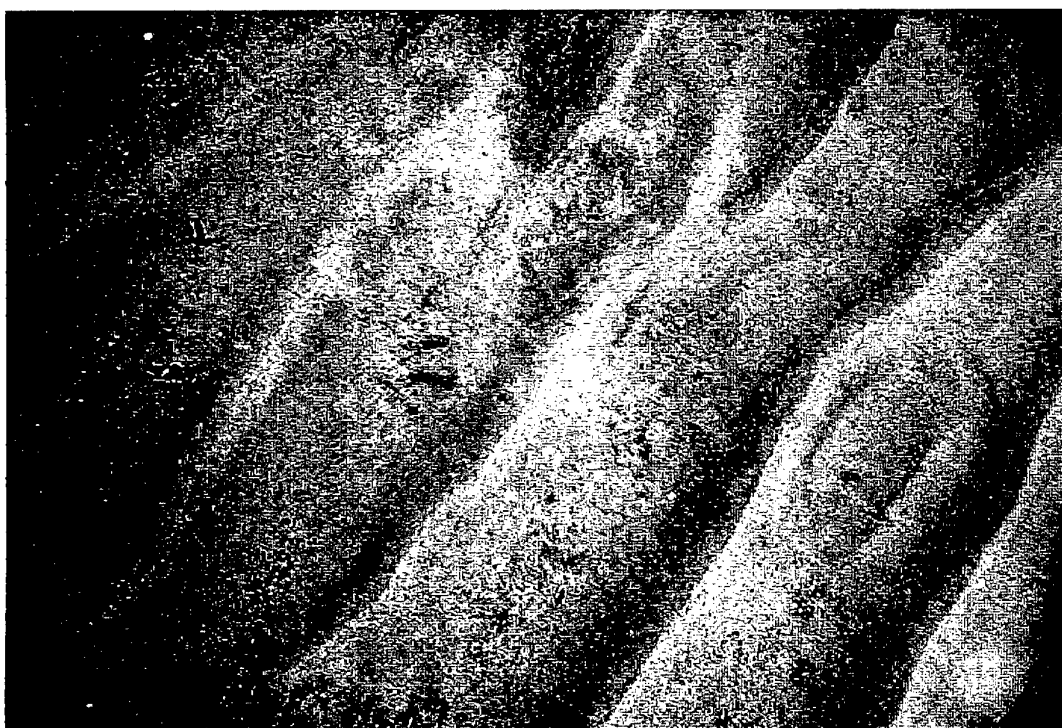
Figure 1 *Photograph of the rippled, sandy seafloor of Biodola Bay, Elba Island, Italy.*

2

Roughness measurement system

SACLANTCEN has recently developed a digital close-range photogrammetry system with an image acquisition system based on the flexibility and low cost of charge-coupled device (CCD) cameras. The system uses stereo images of the seafloor taken with the digital cameras and photogrammetric processing software to produce surface elevation models in a digital format, i.e., digital elevation models (DEMs). Secondary analysis can then be carried out on the DEMs such as the estimation of height and slope distributions, estimation of two-dimensional spectra, or estimation of rms radius of curvature. Some of the advantages offered by the digital photogrammetric system over traditional analytical systems are: (1) stereo images can be acquired and measurements carried out in near real time; (2) acquired images can be displayed and used for measurements on standard computer display devices with no optical or mechanical requirements; (3) the measurement systems are stable and need no recalibration; (4) image enhancement, such as equalization, can easily be applied to the original images to facilitate later processing by increasing the dynamic range of pixel values; (5) corrected images are not necessarily required as any distortions of the images can be taken out through mathematical transformation. The quality of results from a digital image based system, however, like its standard film camera counterpart, will also be affected by various environmental conditions such as water turbidity and sediment color. An end-to-end digital stereo photogrammetry system allows two-dimensional descriptions of seafloor roughness to be obtained relatively quickly, and additionally offers the possibility of integrating and automating data collection and processing. The full photogrammetry system consists of two major components: (1) the image acquisition system which includes the frame, waterproof housings, serial communication cables, digital cameras, and a personal computer running the acquisition software and (2) the image and photogrammetric processing system which includes image enhancement, registration, and stereo-correlation software running on a personal computer (which can be the same computer that was used for the image acquisition).

2.1. Image acquisition system

The cameras used in the system for which results are presented in this paper are inexpensive off-the-shelf Kodak DC50 Zoom digital cameras. In digital cameras the common solid-state imaging device known as a charge-coupled device (CCD) creates the digital images. The CCD sensor consists of a two-dimensional array of closely spaced highly-photosensitive semiconductor elements which change light into electrical signals that are converted and encoded into digital data for digital still photography. The individual CCD elements in the sensor array are analogous to pixels in a digital image array. The CCD has the advantages of low noise, high dynamic range and good

reliability at a low cost compared to other solid state sensors. The DC50 Zoom digital camera uses a Kodak KAF-0400C image sensor with a resolution of 756 x 504 pixels. This image sensor uses a full-frame transfer CCD sensor and elements with a square shape. This is one of the simplest structures for a CCD sensor but is advantageous for photogrammetric applications as it gives improved sensitivity and area utilization rates approaching 100 percent. When using digital cameras for photogrammetric purposes, fiducial marks are not necessary because the regular array of light sensitive elements within the CCD image sensor can be used as a photo-coordinate system.

The two digital cameras are mounted on a frame in containers, which are watertight to 100 m depth and are connected by a serial cable to a shipboard computer for real-time acquisition of digital images (Fig. 2). The exact relative orientation in space of the two cameras is controlled and known exactly in order to make accurate millimeter-scale photogrammetric estimates of seafloor roughness from stereo pairs. It is not usually convenient to set up the cameras with their axes parallel, because this limits the region of space in which objects are visible in both images. It is more normal to aim the cameras so that their axes are angled inwards and converge on the seafloor patch of interest. A convergent geometry allows a large base-to-height ratio, which is generally required to accurately estimate the height field of seafloors that have moderate relief. The stereo camera system used in this study had a base-to height ratio of 0.35. In order to achieve the base-to-height requirement and also to insure 70 - 100 percent overlap of the stereo images, the cameras inside the containers are fully adjustable with the capability of having a variable separation distance between 20 - 60 cm, a variable height above seafloor between 60 - 160 cm, and a variable camera tilt of between 0 - 10 degrees. A strobe or constant, high-intensity lamp was attached to the frame for use as a light sources when needed for taking underwater photos in low-light conditions.

2.2. DEM production

Viewing a scene from two (or more) different positions simultaneously allows the 3-D structure to be inferred, provided that corresponding points in the images can be identified. Humans visual systems make use of this fact, as do photogrammetric systems. The correspondence problem in close range digital photogrammetry concerns the matching of points in two images such that the matched points are the projections of the same point in the scene. Stereo disparity of the point is the difference in the horizontal positions of the images of a point. With knowledge about the transformation between the two cameras, a map of disparity can be obtained from the matching stage that can then be used to compute the 3-D position of the scene points. The final product is the full 2-D height field, or DEM, which has several advantages to previous techniques, such as allowing the full 2-D
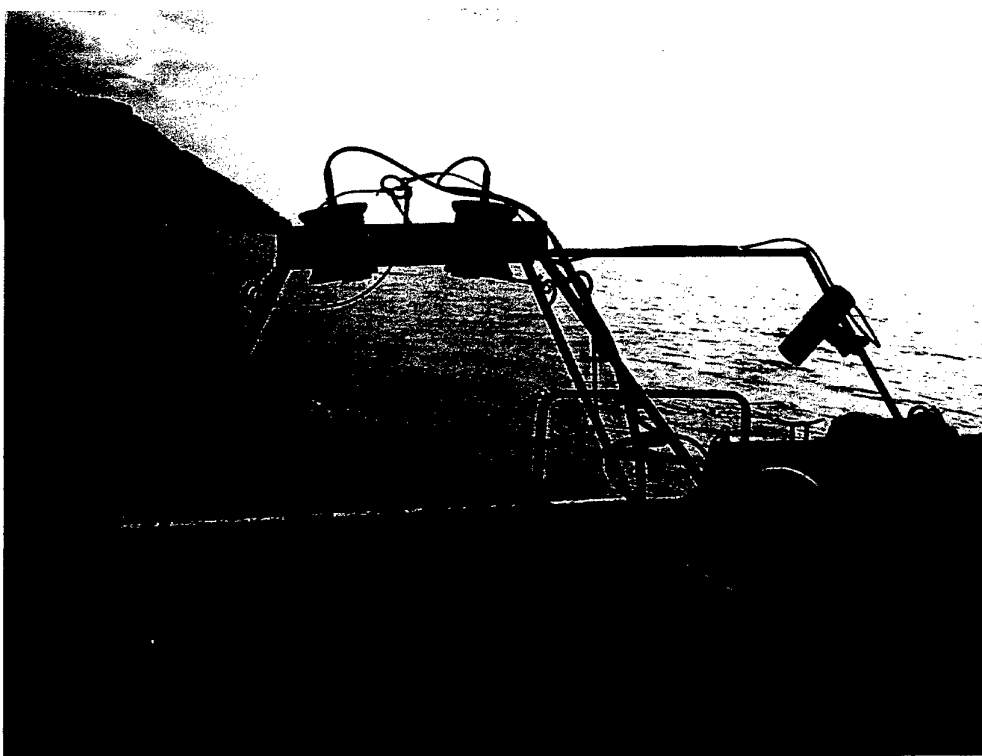
Figure 2 *Underwater components of stereo camera system.*

spectrum to be estimated. Several steps are necessary, however, before the final height field can be obtained from a pair of digital photos, including image rectification and stereo-correlation. A good general review of these two procedures and of close-range photogrammetry in general can be found in Atkinson [7]. An overview of the steps and software involved in processing the stereo images is given below.

An important step in the process of DEM production is known as rectification and is essential when using images taken with cameras in a convergent or non-parallel geometry. Given a pair of stereo images, rectification determines the transformation of each image plane such that pairs of conjugate epipolar lines (lines in the images on which its corresponding points must lie) become collinear and parallel to one of the image axes. The rectified images can be thought of as acquired by a new stereo rig, obtained by rotating the original cameras around the optical center so that both cameras are parallel and looking straight down at the same part of the seafloor. This step is simply the estimation and removal of the effects of relative camera orientation. The transformation parameters can be estimated by using known corresponding points on the two images of a stereo pair. Once the camera orientation parameters are found, the photos are corrected pixel by pixel to remove the effects and produce registered images. The important advantage of rectification is that computing matching points, a 2-D search problem in general, is reduced to a 1-D search problem, typically along the horizontal lines (now epipolar lines) of the rectified images, which will greatly increase the efficiency of the process.

When a pair of stereo images that have been referenced to a common height, or datum, are placed in register, residual planimetric differences in the horizontal coordinates are assumed to result from relief displacement. The differences in x-parallax may then be used to derive relative elevations or height differences by utilizing a computational technique known as automatic stereo-correlation. Automatic stereo-correlation is the automated process of determining the position of corresponding points on two images and is analogous to a human operator measuring corresponding points by setting the floating mark onto the surface of a stereo model. A simple technique for finding corresponding points on two registered stereo images is known as area-based matching. Area-based matching searches a sub-window in the two images by comparing an even smaller sub-window until the correlation is maximized. The points that have maximum correlation are considered to be the same point on both images. Several factors influence the final accuracy of correlated DEMs, including in large part the base-to-height ratio, but this kind of technique should yield rms errors on the order of a pixel [7]. The effective resolution of the system as configured here is on the order of a millimeter in both the horizontal and vertical. Automated photogrammetry algorithms also allow the possibility of self-calibrating a digital stereo camera system. If control targets with fixed coordinates are incorporated into the solution, then the data can be used both for the measurement of camera orientations and locations while simultaneously taking into account camera calibration parameters such as lens distortion. The self-calibration technique does not require any object space control for the method to be effective as a means of camera calibration.

At present, Unix-based workstations comprise the majority of digital photogrammetric platforms. In spite of their high cost, the effectiveness of these systems makes it likely that they will eventually replace analytical plotters. Because PCs are evolving faster than Unix workstations and are more cost effective, an alternative PC-based photogrammetric processing system, the Desktop Mapping System (DMS) by R-Wel Inc. [8], was chosen to perform stereo-correlation calculations. The DMS is a low cost software package that facilitates image processing for remote sensing, and GIS applications using off-the-shelf personal computers and provides a rigorous softcopy photogrammetric solution. The original stereo-correlation algorithm developed for the DMS was designed for use with digital stereo images from the SPOT satellite and makes use of the stereo-correlation technique of area-based matching. The algorithms employed by the software have been used in other close range photogrammetry applications and appear to be quite effective [9].

2.3. Bias reduction on spectral estimates

The height field is, for our purposes, often not the ultimate product of interest. A statistical characterization of the height field is required. For this task the power spectrum is often used, the estimation of which has its own set of problems. Bias (sometimes referred to as "spectral leakage") is a common problem in non-parametric spectral estimation, and is caused by the finite size of data segments used for analysis. Data "tapering" [10] (or "windowing") is often used to mitigate bias effects. Data segments under consideration are multiplied by a tapering function before being Fourier transformed to the frequency domain. While reducing bias, data tapering also causes a reduction of resolution, or a smoothing effect, in the spectral estimate. In general, as data tapers become narrower, bias is reduced and the spectral estimate is less resolved. In our application, it is important to eliminate bias so that a power law function of the spectrum can be accurately estimated. It is also important to maintain spectral resolution so that the frequency of any harmonic components can be estimated. It is desirable then to apply the widest data taper that reduces bias to an acceptable level. The zero'th order discrete prolate spheroidal sequences (DPSS) comprise a convenient family of parameterized data tapers for examining bias/resolution trade-off. A zero'th order DPSS is parameterized by the product NW, where N is the number of points in the sequence and W is a concentration bandwidth (see ref. [10] for a complete discussion of DPSS). Figure 3 shows an example of a 500 point zero'th order DPSS with varying NW.

The data sets used in this study were analyzed by forming a series of spectral estimates for each height field. As a reference point, the two-dimensional periodogram was computed (rectangular taper function). Then spectral estimates using DPSS sequences with NW = 1, 3/2, 2, 5/2, etc. were computed and plotted (note that two-dimensional data tapers are computed by taking the outer product of one-dimensional tapers for each dimension [11]). At a certain level of NW for each case, it was observed that bias was no longer a factor, and that increasing NW further only had a smoothing effect on the spectral estimate. This limiting NW case was then used as the spectral estimate. Figures

4 and 5 illustrate the application of the 2-D taper to height field data (in this case a taper was used with NW = 2). Spectral leakage is clearly evident in Fig. 4 and is removed in Fig. 5. The associated loss in resolution in Fig. 5 is also evident.
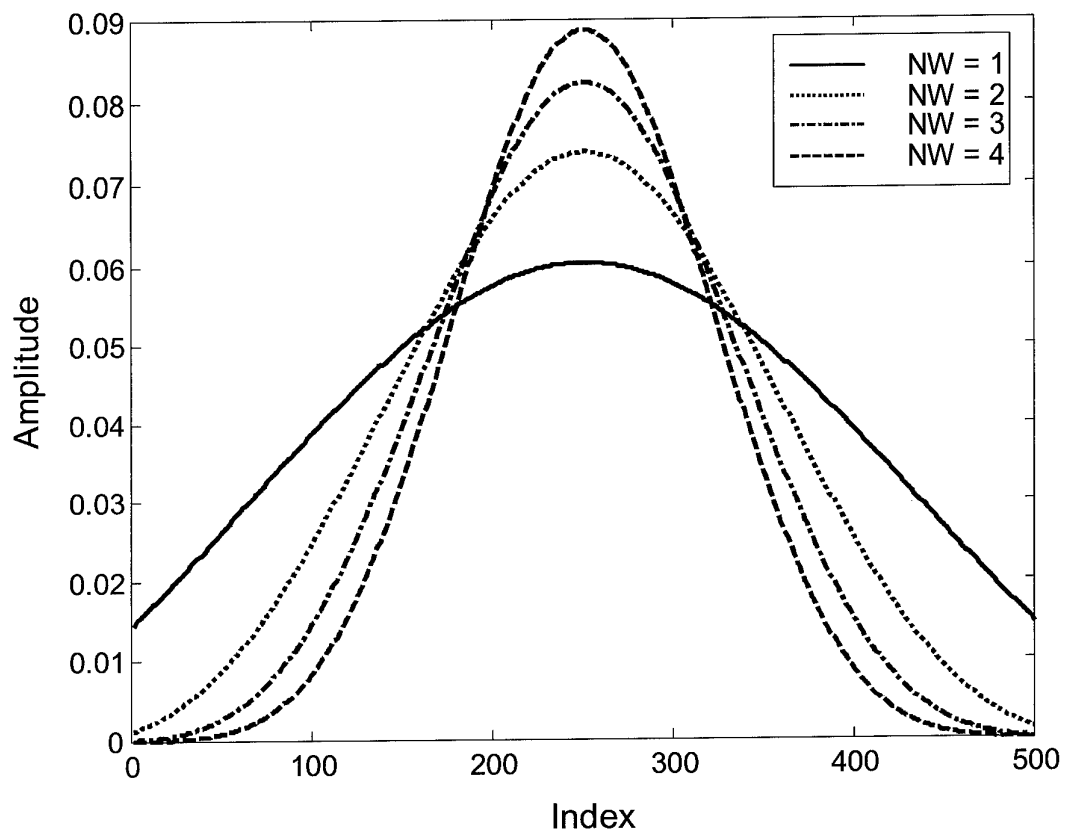
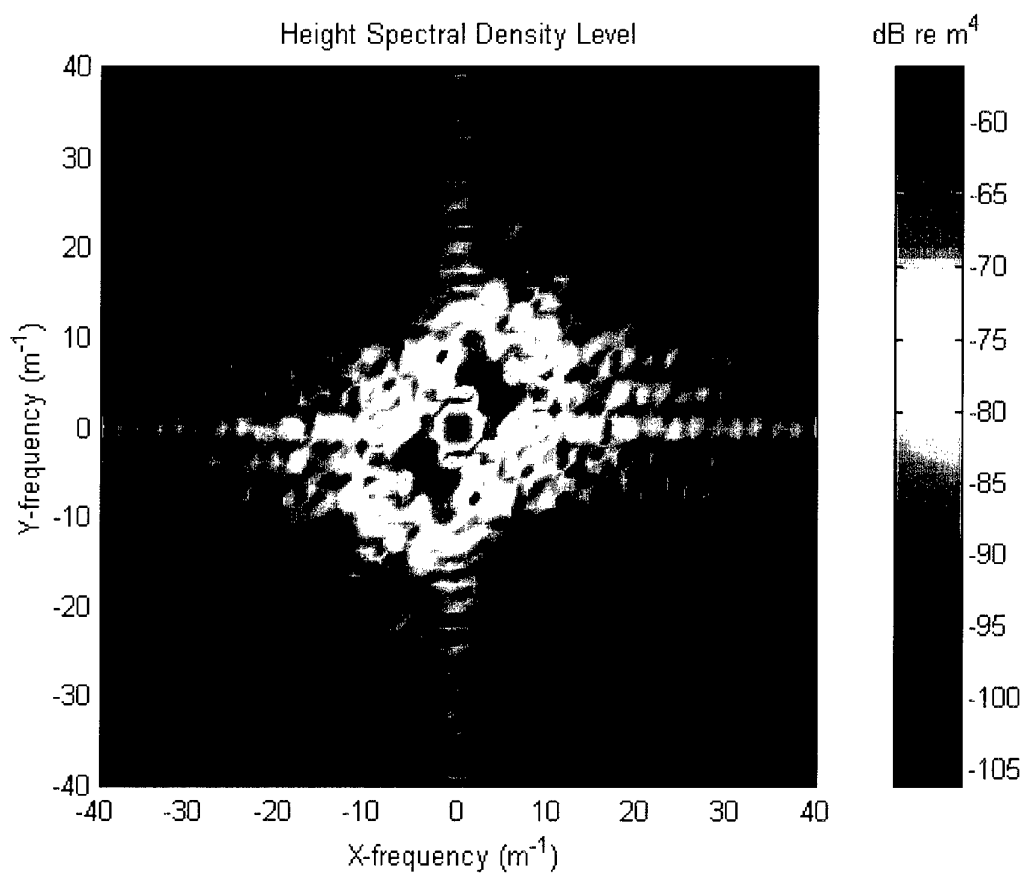**Figure 3** *Example of a 500 point zero'th order DPSS with varying NW.*

Figure 4 *Estimated two-dimensional spectrum made without applying a taper to the original height field data.*
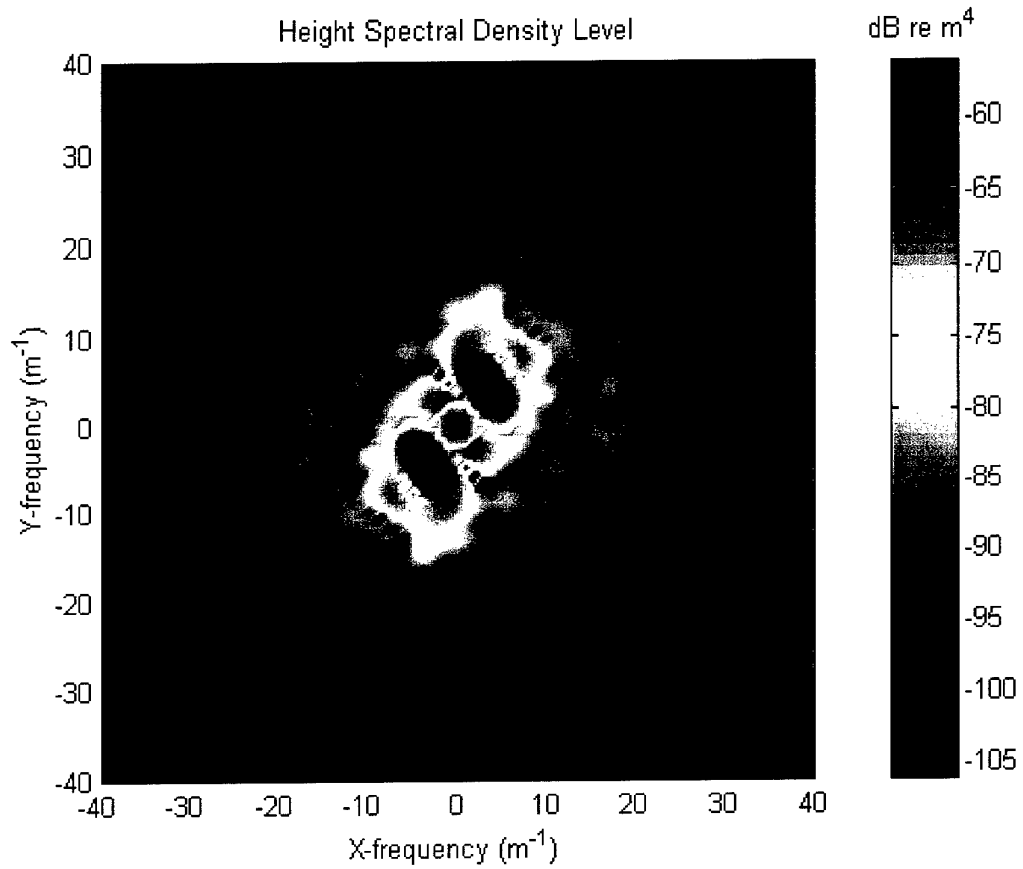
Figure 5 *Estimated two-dimensional spectrum made with an applied taper (NW = 2).*

3

Results and discussion

In order to test the digital image acquisition system and photogrammetric processing software, stereo photos were taken in conjunction with high-frequency acoustic experiments carried out on rippled sandy seafloors near Elba Island, Italy. The first site, Biodola Bay, is located in the Gulf of Procchio, on the northern side of Elba Island. The water depth at this site is about 10 m and the slope of the seafloor is very low (<0.5 degrees). The tidal range in the area is very small (less than 30 cm) so that tidal currents should also be small. Bottom sediments in Biodola Bay consist of well to moderately sorted fine sands. The second experiment was carried out in 13-15 m water depth near Marciana Marina, Elba, also on the northern side of the island. At Marciana Marina, the seafloor is composed of a medium sand. At both sites several meters of sand cover the seabed. During the two experiments, the stereo camera system was deployed and digital stereo images were taken every day at very nearly the same location in order to see daily changes in roughness. Two or three different sets of photos were also taken in slightly different spots at each photograph location to check the stability of roughness estimates. A total of 28 pairs of images were obtained during the first experiment while 15 pairs of digital stereo images were taken during the second experiment.

Examples of photographs taken with the digital cameras at Biodola Bay are shown in Figs. 6 and 7 as are their associated 2-D height fields derived from stereo photos as discussed in the previous section. The sand ripples are easily seen in this pair of figures. The obvious structure of the rippled sand seafloor allows a visual check on the ability of the software to yield correct results on image data. The calculated height field matches exactly the observed ripple structure that is seen in the photographs and displays the common ripples characteristic of sharp crests and broad troughs. Intercalating ripple tips and divergence of the ripples due to the intercalating tips can be seen (Fig. 7) as well as a smaller ripple within the larger main ripples (Fig. 6). The seabed in both figures also displays a mottled appearance and bedform disturbance due to intense bioturbation.

Figure 8 displays the two-dimensional spectrum that was estimated from the seafloor height field of Fig. 7. It is interesting to compare the original seafloor image with its associated spectrum. The two-dimensional spectrum is seen to have an overall tilt in frequency space, with the axis of the maximum values running from the top right to bottom left, corresponding to the average ripple orientations. Upon closer inspection of the spectrum, various individual frequencies are noticed and can be correlated to the ripple wavelengths and directions seen in the digital photographs. Ripples running at a 45 degree angle with a wavelength of approximately 200 mm are seen in the image and this component is also seen in the 2-D spectrum as the deep red patches. Intercalating ripple
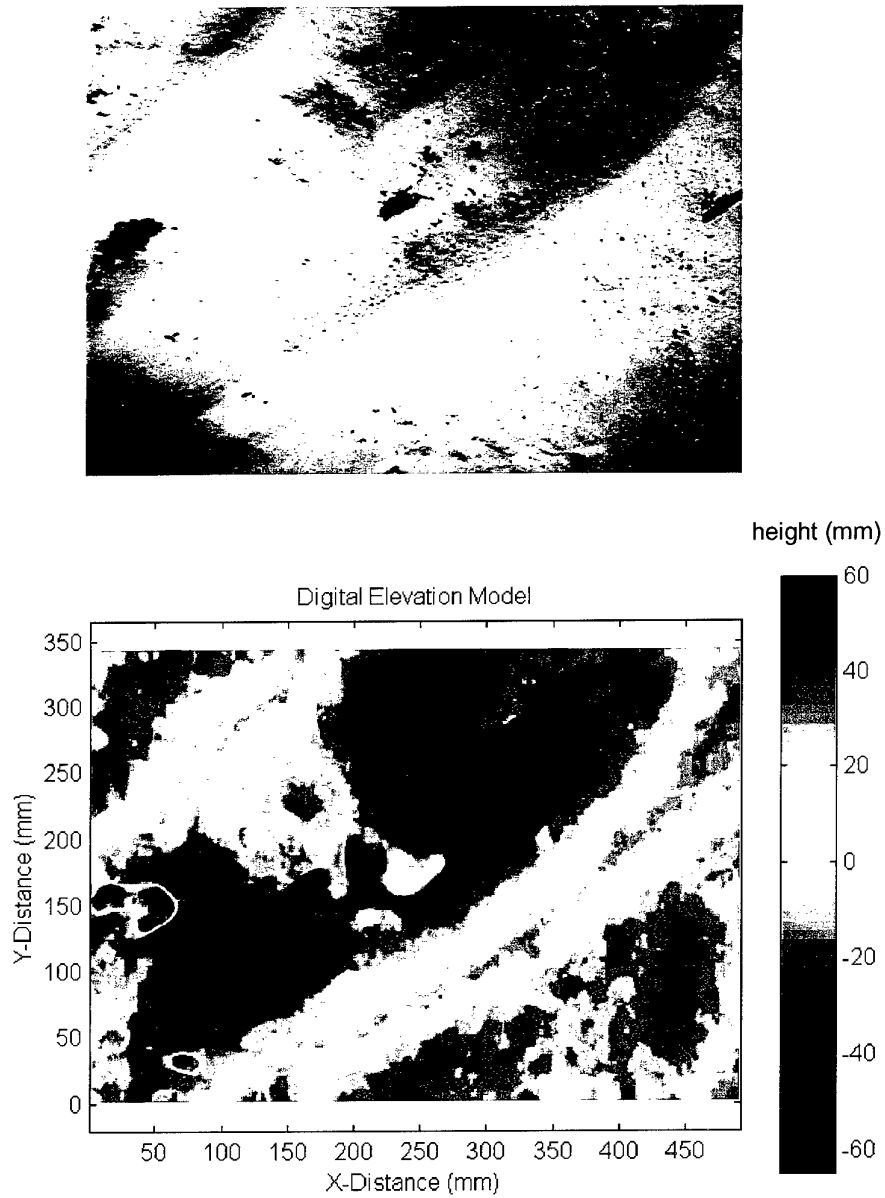
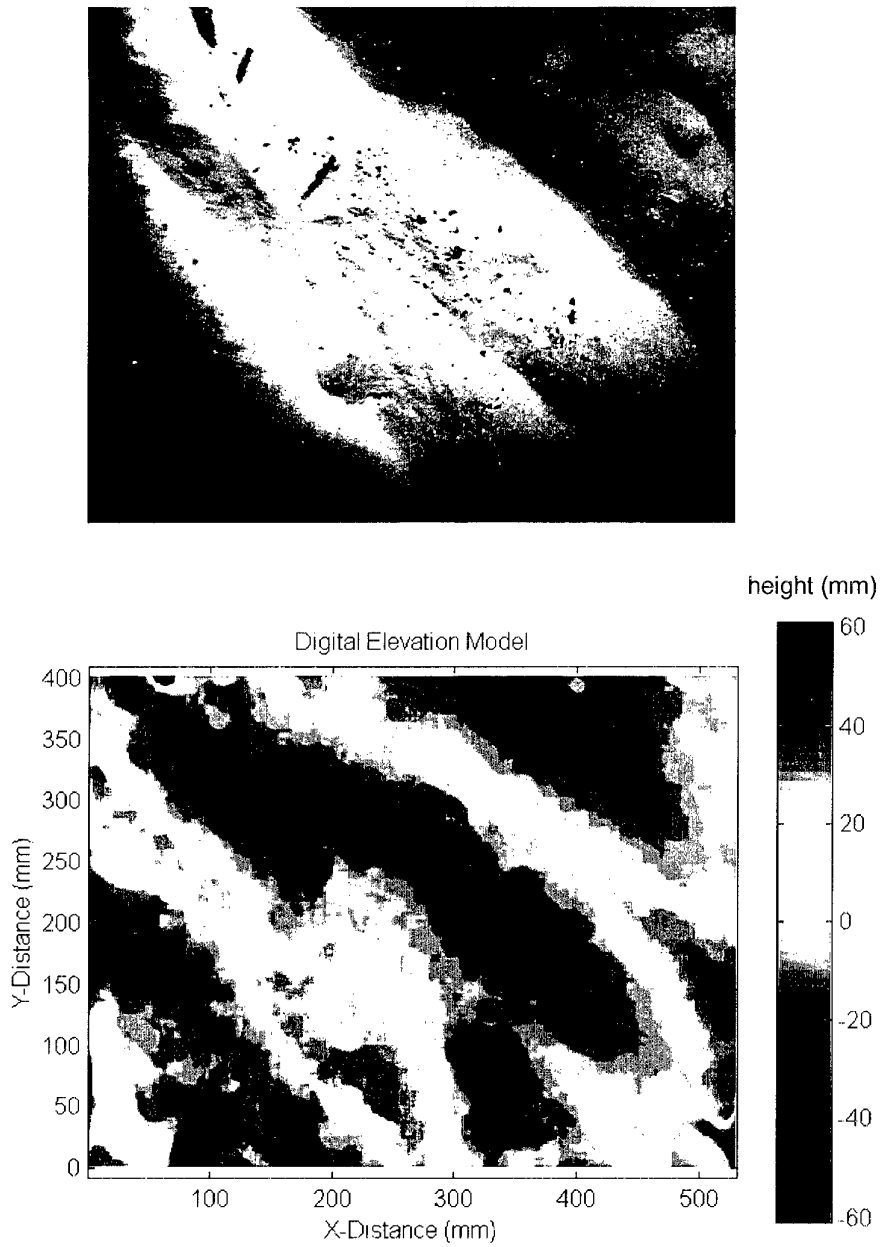**Figure 6** *Example photograph and height field from Biodola Bay.*

Figure 7 *A second example photograph and height field from Biodola Bay taken on the same day and a few meters from the example in Fig. 6.*
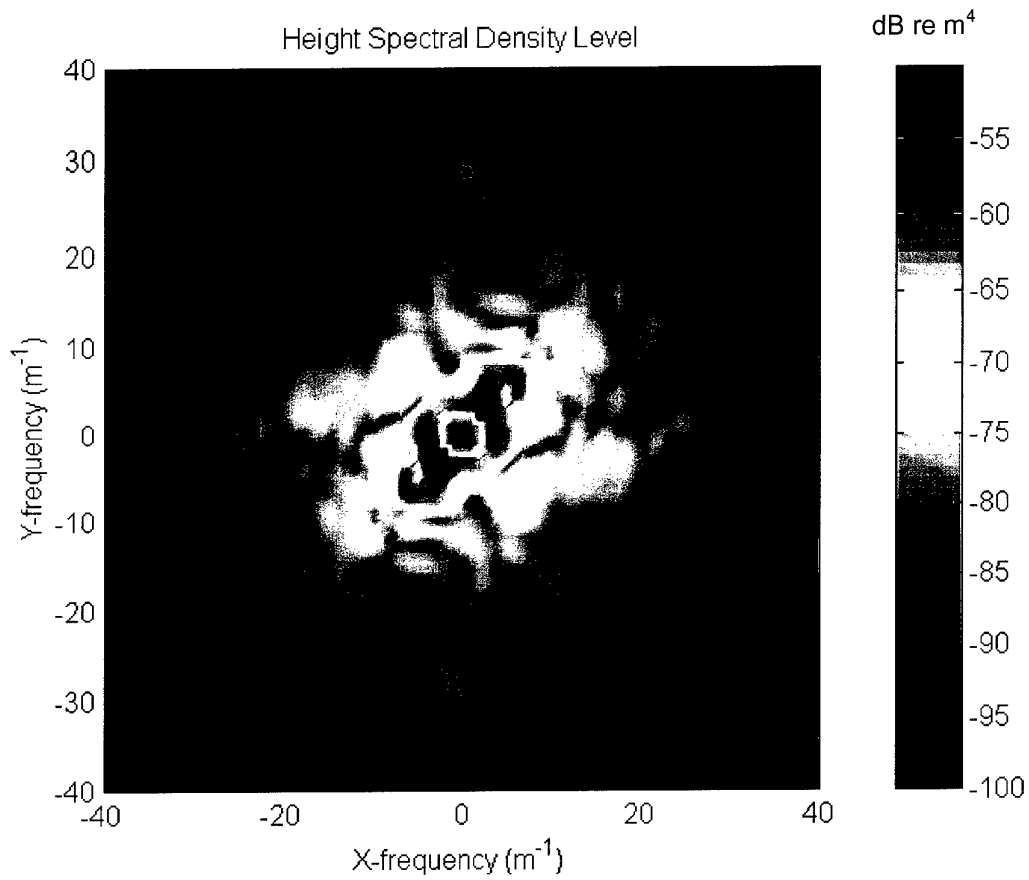
Figure 8 *Two-dimensional spectrum estimated from the height field of Fig. 7.*

tips causing the wavelength to approximately halve can be seen on the right side of the image and correspond to individual frequency components of double the main ripple frequency. This spectrum is obviously not isotropic exhibiting the two sharp peaks of the quasi-periodic component. The influence of the ripples on the spectrum is more easily seen in perpendicular slices of the 2-D spectrum taken across (45 degrees) and along (135 degrees) the ripple direction shown in Fig. 9. The 15 dB discrepancy between the orthogonal slices is apparent. The slice of the 2-D spectrum along the ripples shows power law behavior with a slope of -3.2 over the whole range of data. The slice across the ripple direction shows the dominant frequency is 5 cycles/m (20 cm wavelength) with another peak due to the intercalating ripples at 10 cycles/m (10 cm wavelength). The influence of the ripples on the spectrum seems to stop at about 20 cycles/m where it starts to follow the same power law behavior as the slice taken along the ripples. Below 20 cycles/m the ripple spectrum can be described as a non-centered Gaussian. In spatial terms, the seafloor roughness in this case can be thought of as small-scale random biologically induced roughness riding on larger ripple components.

The next example comes from the Marciana Marina site. The DEM in Fig. 10 shows a range of heights from -2.5 cm to 2.5 cm in agreement with measurements of the ripple heights made by divers on the same site. In this image the seafloor appears somewhat smoother that the images of Figs. 6 and 7. The parallel ripples in the seafloor height field seem to change direction near their tips where they intercalate with other tips. This phenomenon was also seen on underwater video taken at the site and is due to the ripple field having features oriented in two directions. Ripples having this particular kind of structure are known as interference or compound ripples, which consist of two obliquely intersecting sets of ripple crests. Interference ripples result from the modification of one ripple train due to one set of conditions by a later train generated by waves or currents with a different orientation. The 2-D spectrum for this height field example is shown in Fig. 11. The peaks in the spectrum associated with the ripple frequency are elongated due to the change in direction and frequency of the ripples across the image. Figure 12 presents, as before, slices of the 2-D spectrum taken across and along the dominant ripple direction. Although the roughness data were taken a month apart, except for lower overall level, the general shapes of the power spectrum slices are almost exactly the same as those for the Biodola Bay example of Fig. 9. This is not surprising given the similar depths and the fact that in winter there is a consistent dominant swell frequency found in the Mediterranean on the North side of Elba Island. The slope of the power law is in this case -3.4. The ripples, as in the Biodola example, dominate the spectrum for the slice taken across the ripple direction out to about 20 cycles/m where the spectrum joins the power law behavior of the roughness spectrum for the along ripple direction.

Previous work on seafloor roughness has indicated that an isotropic two-dimensional power law [2], [12], [13] can often characterize power spectra. The power spectral representation of interface roughness presents a complete description of roughness as it contains all scaling and statistical information. The general approach has been to fit a power law, $W_p(k)$, to the mean power spectral density:
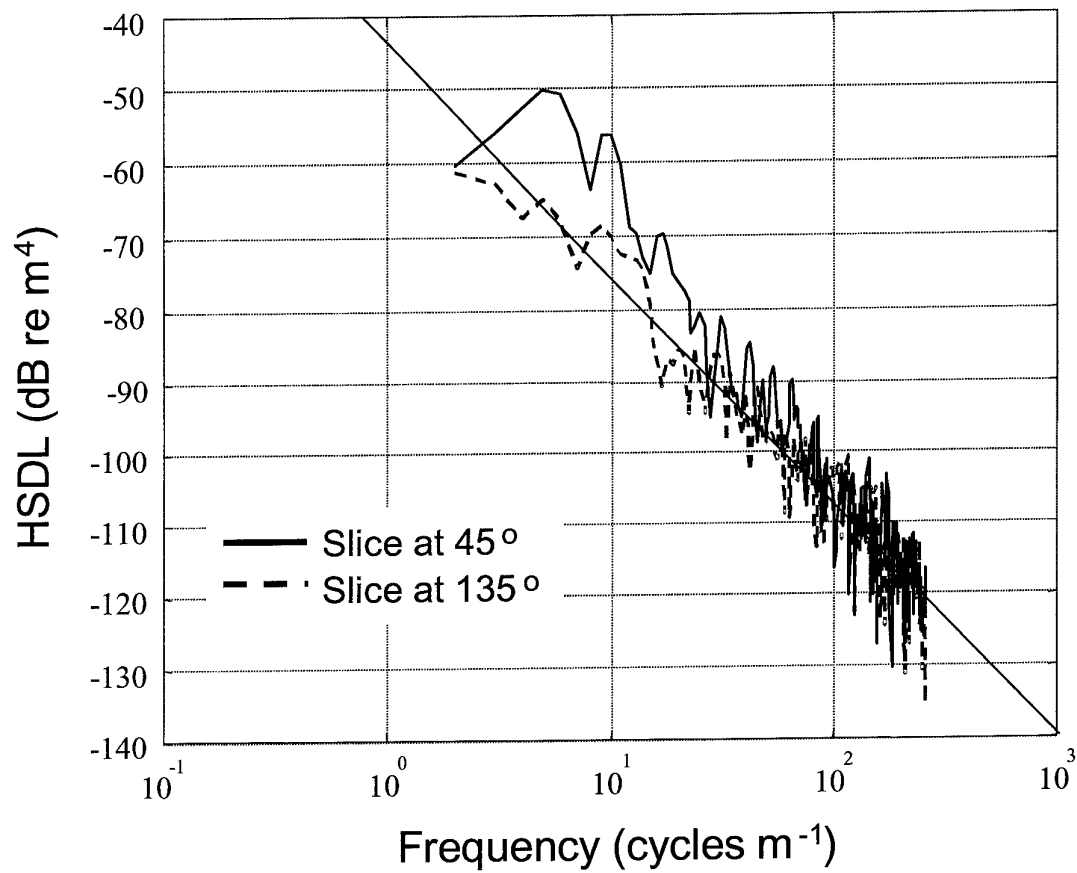
$$W_p(k) = ak^{-b},$$

Figure 9 *Slices of the two-dimensional spectrum of Fig. 8 taken across (45 degrees) and along (135 degrees) the ripple directions. The thin straight line in this figure represents a slope of 3.2.*

Digital Elevation Model

height (mm)

Figure 10 *Height field example from Marciana Mariana, Elba Island, Italy.*

Figure 11 *Two-dimensional spectrum estimated from height field of Fig. 10.*

Figure 12 *Slices of the two-dimensional spectrum of Fig. 11 taken across (45 degrees) and along (135 degrees) the ripple directions. The thin straight line in this figure represents a slope of 3.4.*
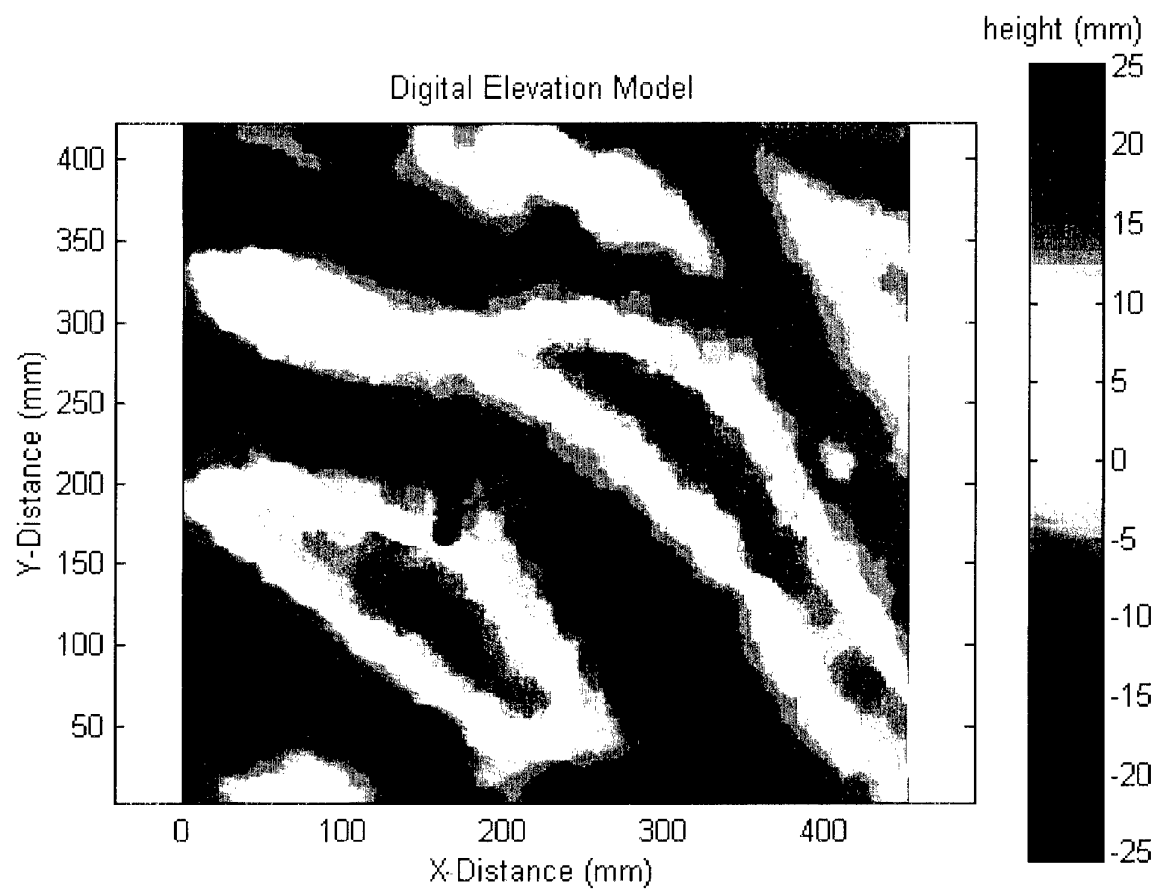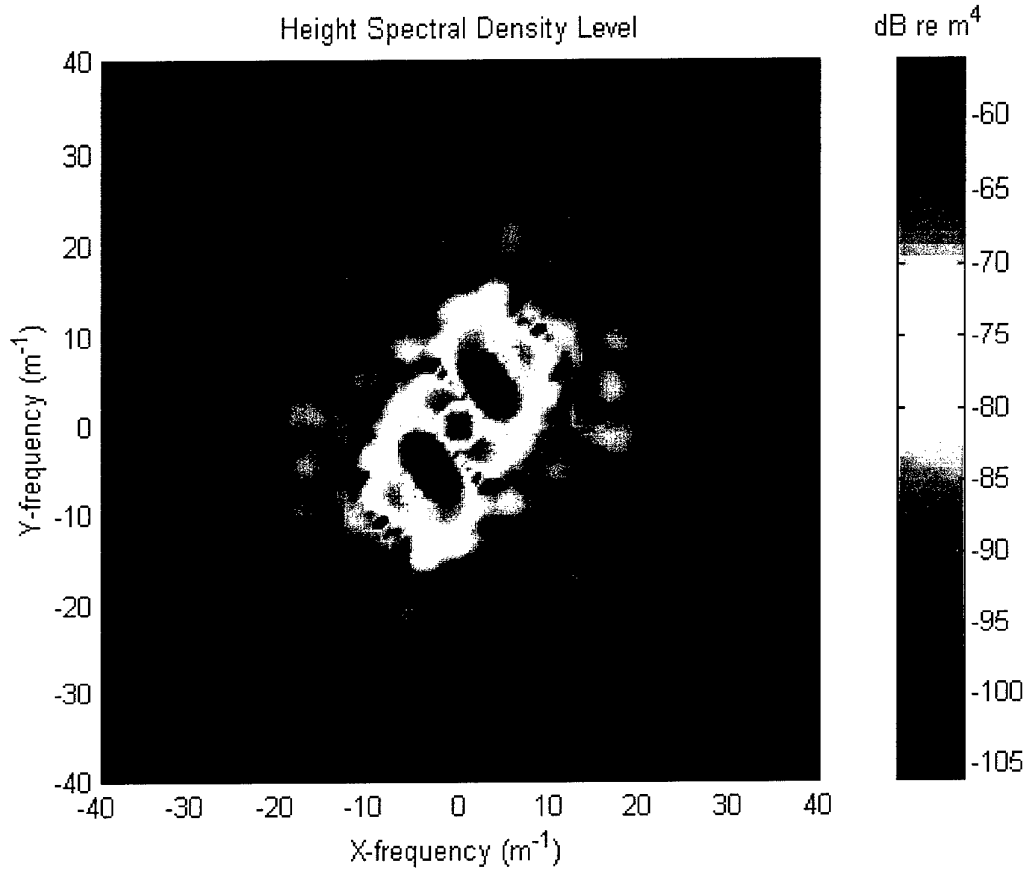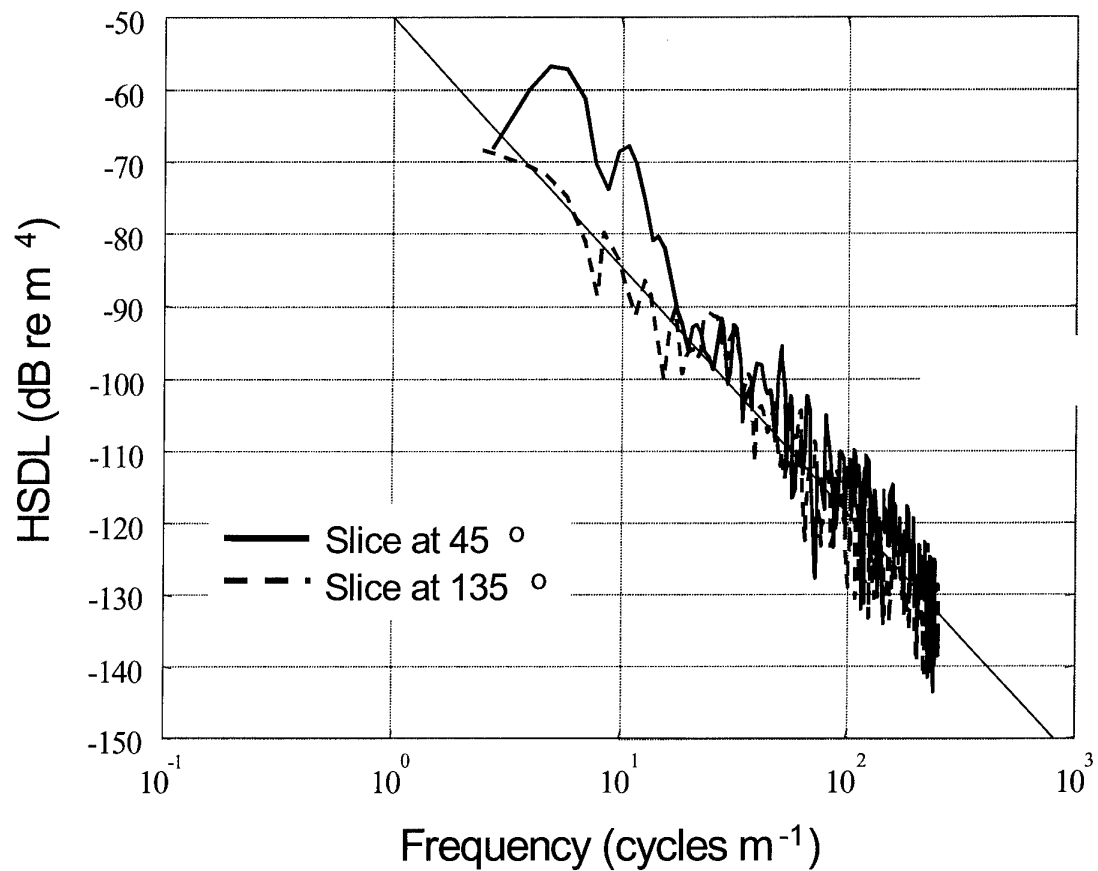
where k is the magnitude of the two-dimensional wave vector. This equation is linear in log-log space:

$$\log(W_p(k)) = \log(a) - b \log(k).$$

In this representation, only two parameters of the power spectrum are needed to completely describe roughness: the offset, $\log(a)$, which gives the strength of the spectrum and the slope, b. For natural, random sediment surfaces the value of the slope parameter has been found in almost all cases to be between 3 and 4. The rms height of the surface is related to the area under the spectrum and so is positively correlated with $\log(a)$. Briggs and Ray [14] have obtained good fits with the power law to photogrammetrically derived roughness spectra from 1 cycle/m to 100 cycles/m, and Fox and Hays [13] showed evidence of power law behavior for roughness in the 2 mm to 200 m wavelength range.

The isotropic power law representation also seems to work well for the data presented in this paper at high frequency (above 20 cycles/m). For frequencies lower than 20 cycles/m, however, the influence of quasi-periodic features needs to be included. Estimated roughness spectra from real ripple fields suggest that for shallow-water seafloors the two-dimensional roughness spectrum can be better approximated by a two component model, consisting of a power law component and a quasi-periodic component described by a non-centered Gaussian as presented in Pouliquen, et al. [15]. To include the effects of the ripples we modify the roughness spectrum by adding a Gaussian component, $W_g(k)$, which describes the quasi-periodic nature of the seafloor

$$W(\mathbf{k}) = W_p(k) + W_g(\mathbf{k})$$

The Gaussian component is given by

$$W_g(\mathbf{k}) = Q(\mathbf{k}, \mathbf{k}_c) + Q(\mathbf{k}, -\mathbf{k}_c),$$

where the spatial frequency $\mathbf{k}_c = (k_{xc}, k_{yc})$ defines the average ripple wavelength. Q, which has the properties of a joint probability distribution function, is given by

$$Q(\mathbf{k}, \mathbf{k}_c) = \frac{l_x l_y \eta^2}{4\pi} e^{-\left(\frac{l_x^2 (k_x - k_{xc})^2 + l_y^2 (k_y - k_{yc})^2}{2}\right)},$$

with k_x and k_y being the components of wavenumber, and l_x and l_y the components of the correlation length. The parameter η allows the roughness variance to be specified independently of $\mathbf{k}_c$. The strength of anisotropy is a function of $\mathbf{k}_c$, l_x, and l_y and when $\mathbf{k}_c$ is set to (0,0) and $lx = ly$ the seafloor has no directional features. The integral over all $\mathbf{k}$-space of the power spectrum, W, is equal to the variance of the 2-D surface heights. Although few studies of high-frequency acoustic scattering have been carried out on the kinds of seafloors studied in this paper, there is some evidence of the anisotropy of mean backscattered power due to ripples [16]. The isotropic power law is usually assumed in scattering models because of its simplicity. This spectrum model will be insufficient for describing directional dependence of scattering from rippled seafloors, and will have to be replaced with an anisotropic 2-D model such as that put forward in this work. Additionally, to effectively model other statistical properties of scatter such as the amplitude distribution the effects of directional features will need to be included.

Although not included in the spectrum description above, the true seafloor height field will be a function of time. For a seafloor roughness spectrum well described by an isotropic power law, such as might be found in deep water, the spectrum might not have strong time dependence, even though a particular surface might be continually changing. For this case a given acoustic image or 'snapshot' of the seafloor, as in Dworski and Jackson [6], will change over time while average scattered levels should be constant. In shallower water with ripples the situation will obviously be more complicated. A likely scenario is that the seafloor is formed into ripples rather quickly so that the spectrum is completely described by a non-centered Gaussian. After the wave forcing is removed the ripples start to be modified by biology so that the spectrum is described with two components (which is the case seen in the examples given in this paper). After more time passes the ripples will be reduced so that the spectrum becomes completely power law. Thus the seafloor changes over time from being strongly anisotropic to being isotropic.

Ripple fields will, in general, not possess Gaussian statistics because of their inherent asymmetry - broad troughs and narrow peaks. The asymmetry yields distributions skewed towards negative heights, although the height distribution may over time tend to Gaussian statistics as peaks are smoothed into the troughs. An example profile (taken from Fig. 10) of the general shape of the ripples seen in this study is given in the top graph of Fig. 13 (solid line). It is immediately apparent that these ripples can not be approximated by a simple sinusoid. The ripple shape most closely resembles that of a Stokes wave, which is an approximation of the shape of water waves in finite depth [17]. To third order, the Stokes wave surface height, h, can be described by

$$h = -a \cos kx + \frac{1}{2} ka^2 \cos 2kx - \frac{3}{8} k^2 a^3 \cos 3kx,$$
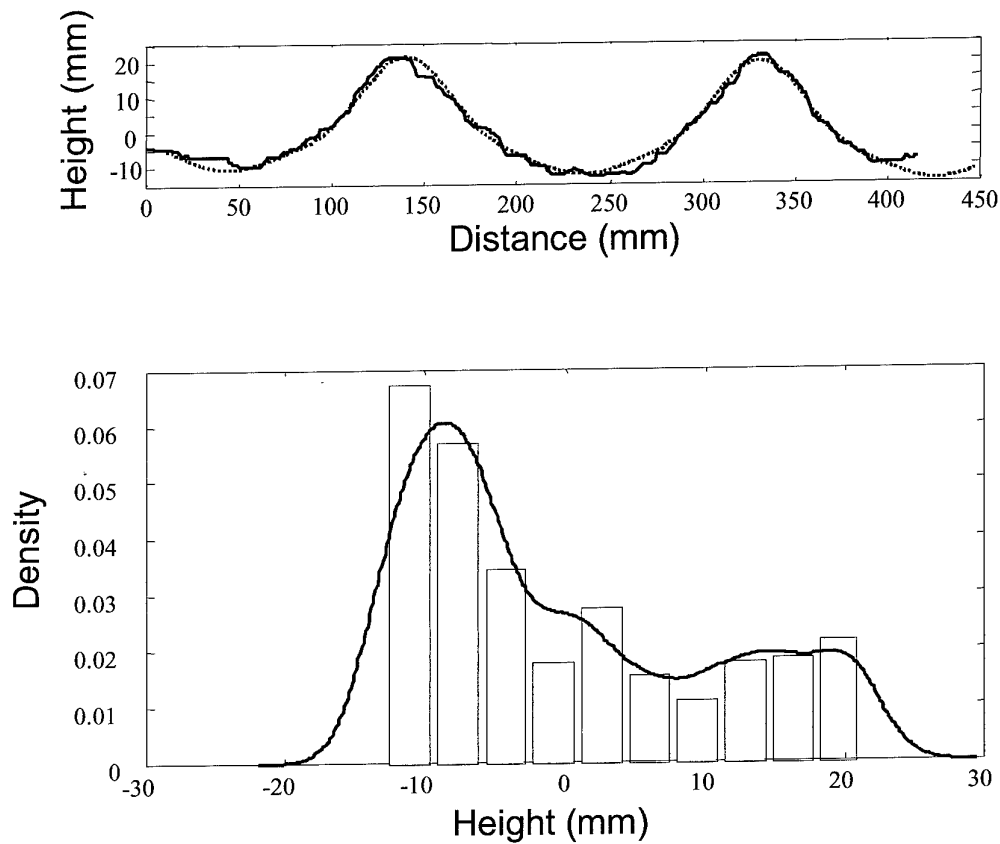
Figure 13 *(Top) Profile taken across ripples of Fig. 10 (solid line) and a Stokes wave profile (dotted line); (bottom) Distribution of heights for the DEM given in Fig. 10 (histogram) along with the kernel density estimate of the distribution (solid line).*

where k is the spatial wavenumber and a is a parameter of the polynomial expansion. The height distribution given in the bottom graph of Fig. 13 is decidedly non-Gaussian with values skewed as expected toward negative values. Along with the histogram is plotted the kernel density estimate (KDE) of the distribution. The KDE can be thought of as an alternative to the histogram that avoids some of its drawbacks, such as lack of smoothness and dependence on the origin.

The peaked shape of the profile presented in Fig. 13 has additional implications for high-frequency acoustic scattering, potentially affecting multiple scattering, shadowing, backscattering enhancement, and scattered amplitude statistics [18]. The top profile in Fig. 14 displays a profile taken from a DEM from the Marciana Marina data set. The remaining profiles are simulated using the magnitude information from the power spectrum together with uniform random phase. Visual inspection of the bottom profiles shows that the simulated profiles, while looking somewhat rippled, do not reproduce the characteristic sharp Stokes shape of the top profile. The power spectral density formulation of surface heights has inherent limitations in describing these complex surfaces and clearly requires the information contained in the phase of the Fourier transform, as it is the phase characteristics that control the organizational characteristics of the surface. Unfortunately, the phase aspect of a frequency domain representation of the surface exhibits a non-random variation with frequency.
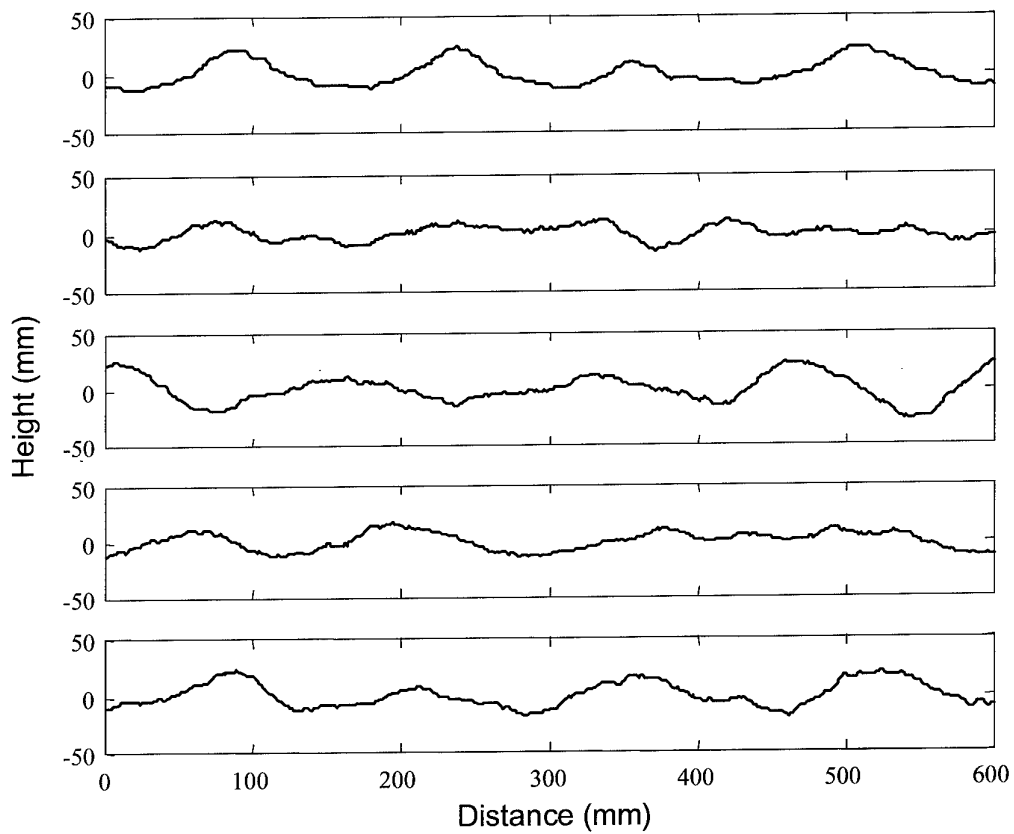
Figure 14 *A real ripple profile estimated from stereo photographs is given in the top frame and realizations of profiles made using the amplitude spectrum of the original profile and random phase are shown in the four frames beneath.*

4
Summary and conclusions

The availability of inexpensive CCD cameras and advances in personal computer based photogrammetric processing of digital images have greatly improved our ability to quickly obtain quantitative, two-dimensional estimates of seafloor roughness. The high-resolution data obtained with this system were used to study and characterize anisotropic (rippled) seafloors at Elba Island, in Tuscany in western Italy. Results of these measurements have shown that sediment surfaces in shallow water are often anisotropic and should be modeled with two-dimensional statistical models. A one-dimensional description, such as the slope and offset of a power law representation of the power spectra will not give a sufficiently complete description of seafloors having oriented features. A better statisitical model of the two-dimensional roughness spectrum for a natural rippled sediment surface was found to be a two component spectrum comprised of a non-centered Gaussian component and an isotropic power law component. The proportions of the two components will most likely be time dependent with the quasi-periodic component of the ripples dominating immediately after their formation and eventually disappearing due to continuous 'randomization' of the interface by benthic animals. The profiles of rippled seafloors were also found to not exhibit Gaussian height distributions. Both the anisotropic nature of rippled seafloors and their non-Gaussian height distributions have the potential to affect strongly high-frequency seafloor acoustic scatter. Additionally, the assumptions of Gaussian statistics and isotropy often made when modeling high-frequency scattering will be incorrect for many shallow-water seafloors. Natural ripples tend to be sharp-featured at least for some time after their formation. For characterization of these sharp features, phase information in the spatial frequency domain is required, as this controls the shape characteristics of a surface. Sharp features may also influence acoustic characteristics such as multiple scattering, shadowing and diffraction.

In the future, as camera resolution goes up, costs come down and personal computer speed rises, digital photogrammetry will play an even greater role in seafloor studies. The bandwidth of the measurements can be extended into higher spatial frequencies through the use of higher resolution cameras while the possibility of overlapping multiple images offers extension to lower frequencies. The ease of automation (computer control of the entire process) makes this technique an excellent candidate for long term studies of sediment transport and of changes in acoustic response over time. Digital photogrammetry could also contribute to a better understanding of the dynamics of roughness, i.e., the formation and modification of microtopography due to bioturbation, currents or storm events.

5
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Title

Characterization of the two-dimensional roughness of shallow-water sandy seafloors.

Abstract

Surface roughness is a fundamental seafloor property affecting a variety of physical phenomena including sediment transport and the interaction of acoustic energy with the seafloor. Characterization of seafloor surface roughness and its dynamics is therefore essential for understanding and quantifying the influence of sediment microtopography. Field measurements have been taken recently with an end-to-end digital photogrammetry system providing quantitative, two-dimensional seafloor surface roughness measurements on spatial scales of approximately a millimeter to a meter. Results of these measurements have shown that sediment surfaces in shallow water are often anisotropic and/or exhibit non-Gaussian height distributions, both of which have the potential to strongly affect high-frequency seafloor acoustic scatter. For these kinds of surfaces, simple roughness parameters such as rms height or the slope and offset of a power law representation of the power spectra will not give a sufficiently complete description. Two-dimensional statistical models are needed to capture the anisotropic nature of sediments with oriented features, while for seafloors with peaked forms, it is the phase information in the frequency domain that is required, as this controls the shape characteristics of a surface. Characterization of seafloor roughness based on these ideas will be presented using results from the digital photogrammetry system.

Keywords

Seafloor roughness – sand ripples – seafloor scatttering

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